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Extreme Winds over Denmark from the NCEP/NCAR Reanalysis

Helmut P. Frank
Wind Energy Department
Risø National Laboratory
Roskilde, Denmark
E-mail: helmut.frank@risoe.dk

Risø National Laboratory, Roskilde, Denmark
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Abstract An extreme wind analysis of wind speed calculated in the NCEP/ NCAR reanalysis is done for grid points over and near Denmark. Winds at 10 m, 850 hPa, and geostrophic winds at 850 hPa, 1000 hPa, and at the sea level are analyzed.

At 10 m height the expected extreme wind with a return period of 50 years at the North Sea west of Denmark is 27 $\mathrm{m\,s^{-1}}$. It is approximately 11 % less than estimates from observations. However, values at grid points over land in Denmark cannot be compared with observations because the roughness length of these land surfaces is far to big in the model. A transformation to a common roughness length of 5 cm using the geostrophic drag law yields too high values. At points in northern Germany, where the surface roughness of the model is less, the transformed 50-years wind speed is 22–23 $\mathrm{m\,s^{-1}}$, which agrees well with estimates obtained from measurements.

The analyses of the wind at 850 hPa and the geostrophic wind at 850 hPa or 1000 hPa yield very similar extreme winds of approximately 42 $\mathrm{m\,s^{-1}}$. The geostrophic wind calculated from the surface pressure is approximately 45 $\mathrm{m\,s^{-1}}$ in central Denmark. The geostrophic winds at 1000 hPa are slightly stronger than at 850 hPa, which are somewhat greater than the actual wind at 850 hPa. Transformations to a wind at 10 m over a surface with roughness 5 cm with the help of the drag law yield extreme winds, which are approximately 10–12 % less than from surface measurements. The 850 hPa winds and the geostrophic wind calculated from the surface pressure indicate a weak decrease from west to east, whereas the geostrophic wind data at constant pressure levels show almost constant extreme winds across Denmark. All upper-air and and geostrophic wind data show higher extreme winds in northern Germany than in Denmark.

Further investigations are necessary to find out if the underestimation of the extreme wind by approximately 10–12 % is valid in most mid-latitudes.

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Contents

1 Introduction

For the analysis of extreme winds it is necessary to have several years of observations to be able to make a reliable estimate of the wind speed, which can be expected to occur with a return period of 50 years. For many constructions, this wind produces the extreme load for which the building must be designed. Jensen and Franck (1970); Abild (1994); Kristensen et al. (1999) determined the 50-years return wind for Denmark from measurements at different sites. However, in many locations good measurements of over a sufficient observation period are not available. Hence, it would be of great advantage if extreme surface winds could be derived from modeled data.

An analysis of global weather observations with one modern numerical weather analysis and modeling system was and is performed by the U.S. National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996). A main aim is to investigate possible climate trends with one consistent data set without discontinuities owing to changes of the numerical model, which occur during operational weather forecasting. The NCEP/NCAR reanalysis covers more than 50 years world wide. Therefore, it promises a good data base for global estimates of the extreme winds.

Other reanalyses were performed at the European Center for Medium Range Weather Forecasting (Gibson et al., 1997) or at NASA (Schubert et al., 1993). The analyzed periods are shorter and the data was not available. Therefore, they are not used here.

The low resolution of the global reanalysis model and the temporal resolution of 6 hours likely will result in an under-estimation of the actual extreme winds. However, if this under-estimation turns out to be systematic, the extreme winds from the model could be corrected to make global predictions of the expected extreme surface wind.

This report describes an analysis done for an area around Denmark. The data is presented in section 2. Then follows a short description of the method to obtain the extreme wind. Results for the surface wind are presented in section 4. A comparison with observations is attempted in section 5. As the comparison with observations turned out to be not really possible, the wind at 850 hPa and the geostrophic wind at 850 hPa, 1000 hPa, and the geostrophic wind calculated from the surface pressure are analyzed in the following sections. The work is summarized in the last section.

2 The reanalysis data

2.1 Surface wind

The data analyzed first is the predicted wind at 10 m above the surface. It is calculated on a Gaussian grid with a longitudinal resolution of 1.875° and a meridional resolution of approximately 1.91° (see Kalnay et al., 1996, for more details). The surface heights and the grid are shown in Figure 1. Grid points over the sea are white.

The surface wind is a quantity which strongly depends on the model physics. The data analyzed here is a 6-h forecast, not an analysis of observations. Still, as we are not interested in the prediction of the highest winds in individual storms, but only in the statistics of extreme winds, the model winds might yield good estimates of the true extreme winds.

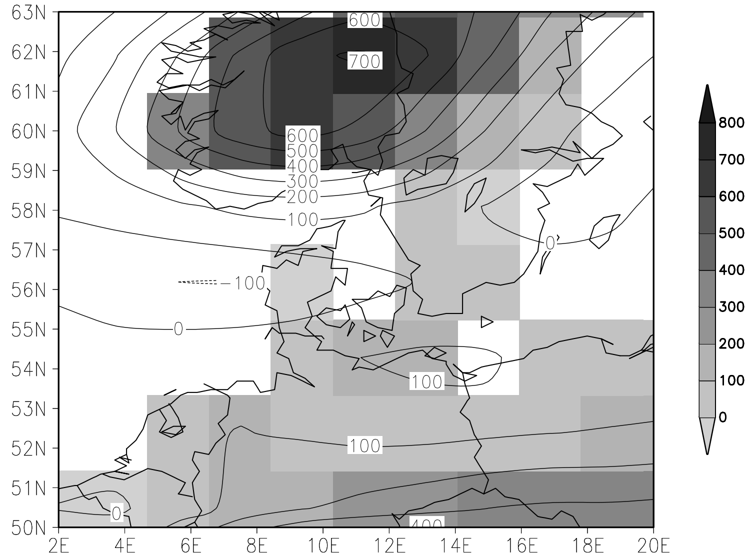

Figure 1. Surface height of the NCEP/NCAR reanalysis model. Grid points over water are white, though their heights are not necessarily zero.

We used wind data every 6 hours for the 52 years 1948 to 1999 for 20 grid points over and near Denmark from 7.5° to 15° East and 52.38° to 58.09° North. The maximum modeled 10 m wind speed for the years 1948 to 1999 is shown in Figure 2. Actually, the 10 m wind of the model is calculated at the height $10\,\mathrm{m} + z_0$, which can be 11 m or more at grid points over land.

The date of the maximum wind is also written on Figure 2. At several longitudes the most severe storm occurs on the same day. However, only at two grid points does the highest wind occur at neighboring latitudes. This indicates the main storm passages from west to east. Most likely, the true maximum speed occurred between the 6 hour sampling interval. As the storm moves eastward its intensity decreases. This can be seen best at latitude 52.4° N.

2.2 Data at constant pressure levels and surface pressure

The data at constant pressure levels, wind at 850 hPa, geopotential height of the 850 hPa and 1000 hPa surface, are available on a regular grid with a resolution of 2.5 degrees in longitudinal and meridional direction. They have been interpolated to the pressure levels and the 2.5 degrees grid from the sigma levels of the model and the spectral representation of the model. The interpolation introduces some smoothing, which reduces any kind of extreme values.

Upper-air winds and pressure or geopotential heights depend more on observations than on the model physics. This is especially the case in Europe with its dense network of observations. Hence, the data represents analyzed observations, not 6 hour forecasts as the surface wind.

Another data set is the surface pressure, i.e. the pressure at the model surface. Like the 10 m wind it is a 6 hour forecast. But, it is influenced by observations. It is available on the same grid as the 10 m wind. A geostrophic wind near the surface can be calculated from it. The disadvantage is that the pressure must be extrapolated to one height, and any interpolation introduces extra uncertainties.

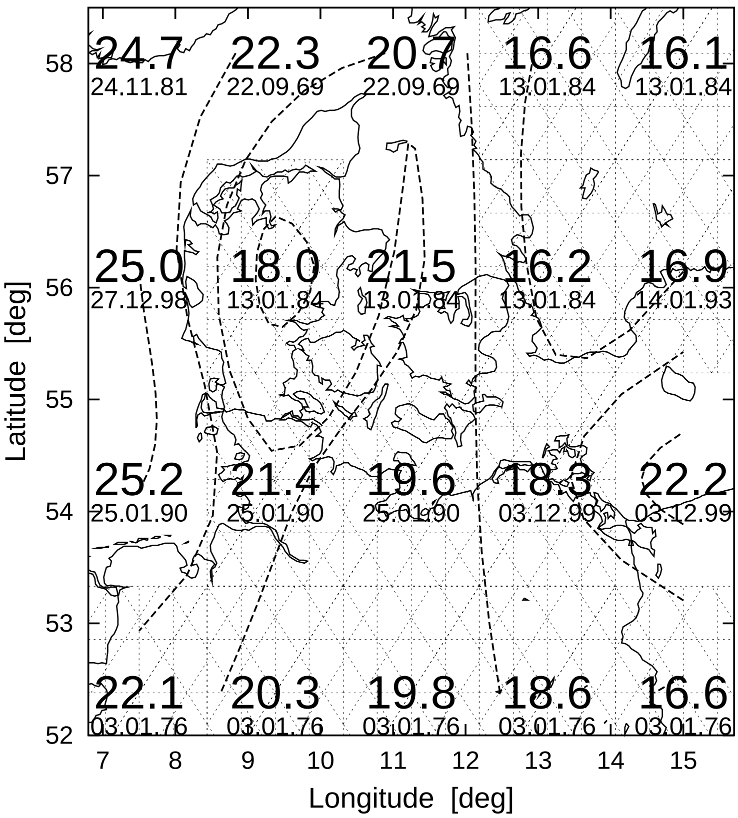

Figure 2. Maximum wind at 10 m for the years 1948 to 1999 of the NCEP/NCAR reanalysis and date of the maximum wind. Grid points over land are hatched. Grid points over water are white.

3 The statistical model

The frequency of extreme events is described by the double exponential, the so-called Gumbel distribution (Gumbel, 1958):

$$P(U) = \exp(-\exp(-\alpha(U-\beta))) \tag{1}$$

$P(U)$ is the cumulative probability that the wind speed, U, is exceeded.

We use the periodical maximum method of Abild (1994) as described by Mann et al. (1998) to determine the parameters α and β. The method is the probability-weighted moment procedure. It is highly efficient for even small-size samples.

A record of the maximum winds $U_1^{\max}, \ldots, U_n^{\max}$ within a certain period is constructed and sorted in ascending order. Here, the maximum wind in one calendar year has been chosen and ordered. From this record the quantity

$$b_1 = \frac{1}{n}\sum_{i=1}^{n} \frac{i-1}{n-1} U_i^{\max} \tag{2}$$

is calculated. Then α and β can be estimated to be

$$\alpha = \frac{\ln 2}{2b_1 - \overline{U^{\max}}} \tag{3}$$

$$\beta = \overline{U^{\max}} - \frac{\gamma}{\alpha} \quad , \tag{4}$$

where $\gamma \approx 0.577216$ is Euler's constant, and $\overline{U^{\max}}$ the mean maximum value.

From the cumulative probability (1) for the recurrence interval $T = 1/(1 - P(U_T))$, the T-year wind speed U_T is obtained:

$$U_T = \alpha^{-1} \ln \ln(1 - 1/T) + \beta \quad (5)$$

The uncertainty of U_T can also be calculated (see Mann et al., 1998).

4 Extreme surface winds from the NCEP/NCAR reanalysis

The one-year maximum winds were determined from the 52 years 1948-1999. Most of the maxima occur in winter (December to February), and none occurs in summer (June to August) (see Figure 3).

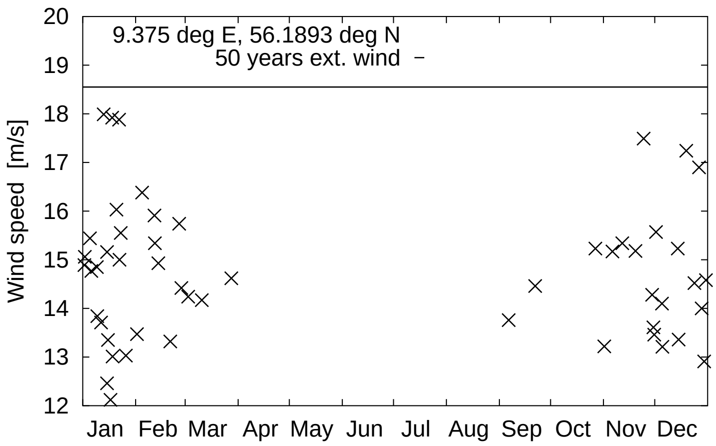

Figure 3. Date of annual maximum wind speed at 9.375° *E,* 56.19° *N of the years 1948–1999.*

The parameters α and β of the double exponential function were fitted to the record of ranked annual maximum wind for each grid point near Denmark. The records are well approximated by this function. (see e.g. Figure 4 and the appendix).

The expected 50-years return wind speed at the grid points was interpolated. Most values are close to the highest modeled wind, which is shown in Figure 2. The values range from 16.1 $\mathrm{m\,s^{-1}}$ at the Polish-German border to 26.6 $\mathrm{m\,s^{-1}}$ in the North Sea west of Denmark (Figure 5). The standard deviations are between 0.6 $\mathrm{m\,s^{-1}}$ and 1.3 $\mathrm{m\,s^{-1}}$. Naturally, the winds are higher over the sea than over land. However, there is a clear decrease from west to east.

Abild (1994) obtained 28.8 $\mathrm{m\,s^{-1}}$ for the expected maximum wind at 10 m above water averaged over 10 min with a return period of 50 years. He transformed the estimate of Jensen and Franck (1970) to 30.3 $\mathrm{m\,s^{-1}}$ for conditions over water. This value had been obtained for Thorsminde at the west coast of Jutland at the North Sea. The grid point in the North Sea west of Denmark has a maximum of 26.6 $\mathrm{m\,s^{-1}}$. However, this data is sampled only 4 times daily. Likely, the true maxima occurred in between the sampling times.

This effect was tested for time series of 10 min mean wind measurements at 44 m, 77 m, and 125 m height at the Risø mast. The original time series were continuous and covered 4 years. The data recovery rate is greater than 99 %. The maximum speeds within 3 months were found and averaged. Taking only the data

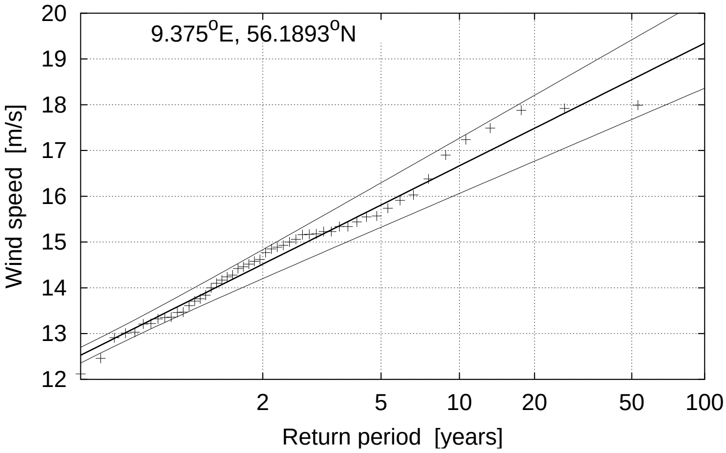

Figure 4. Ordered one-year maximum wind speed at 10 m at 9.375° *E,* 56.19° *N, and the double exponential fit. The thin lines are the fit plus/minus one standard deviation.*

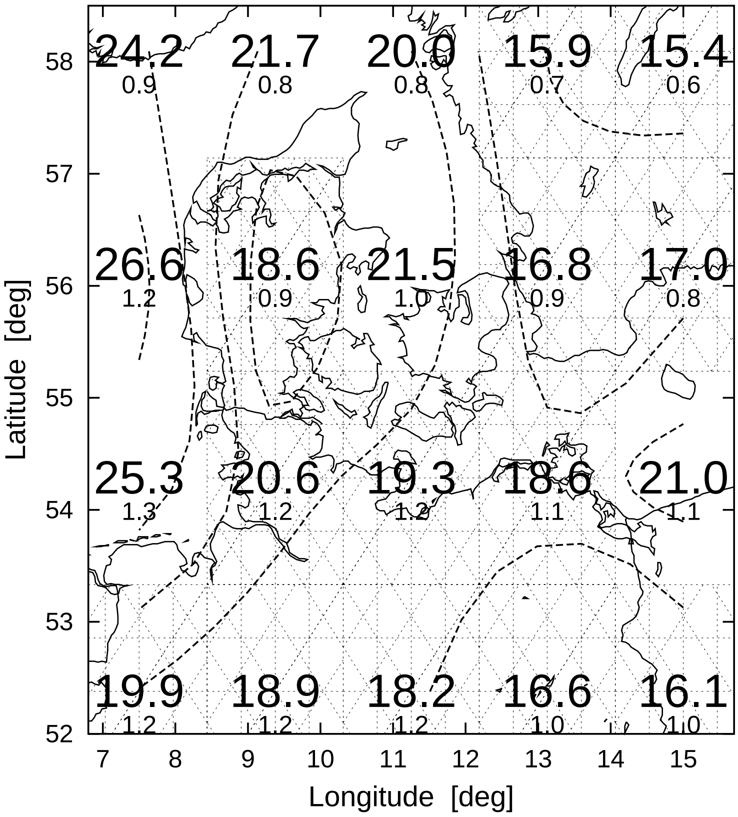

Figure 5. The expected 50 year maximum 10 m wind determined from the NCEP/NCAR reanalysis over and near Denmark. The standard deviation is written below the expected value.

at the hours 0, 6, 12, 18 the average maximum is reduced to between 87.4 % and 88.9 % of the maximum of the full time series. The reduction is slightly less at 125 m than at 44 m height.

Definitively, the variability in the model is less than in nature. The time step of the model is 20 min. However, it is not clear that this truly corresponds to an averaging time of 20 min of measured data. Also spatial averaging may reduce the modeled maxima compared to point measurements. If we correct the model wind by 11 % we obtain 29.5 $\mathrm{m\,s^{-1}}$. This lies between the estimates of Abild and the transformed estimate of Jensen and Franck. The uncertainty margin of our estimates includes both.

5 Surface wind at standard conditions

5.1 Transformation to uniform roughness

The extreme winds obtained in the previous section cannot be compared directly with each other and with observations because the roughness varies from one grid point over land to the other. It must be expected to differ from the local roughness at an observation site, too. Therefore, the modeled winds must be transformed to a common roughness to make them comparable among each other and to observations.

The transformation to one roughness follows the wind atlas method used in the European Wind Atlas (Troen and Petersen, 1989) and applied to extreme winds by Abild (1994) or Kristensen et al. (1999). The friction velocity, u_*, is determined from the 10 m wind speed and the surface roughness length, z_0:

$$u_* = \kappa U_{10} \Big/ \ln \frac{10\,\mathrm{m} + z_0}{z_0} \quad . \tag{6}$$

A geostrophic wind speed, G, is calculated from the friction velocity using the geostrophic drag law (see e.g. Blackadar and Tennekes, 1968)

$$G = \frac{u_*}{\kappa} \sqrt{\left(\ln \frac{u_*}{f z_0} - A\right)^2 + B^2} \quad , \tag{7}$$

where f is the Coriolis parameter and z_0 the roughness length of the surface. A and B are constants for neutral stratification. They are not well known. Values $A = 1.8$ and $B = 4.5$ are used in the European Wind Atlas (Troen and Petersen, 1989), by Abild (1994), or Kristensen et al. (1999). Zilitinkevich (1989) lists a range of 0.9 to 4.7 for A, and 1.8 to 6.1 for B found by different authors. Kristensen and Jensen (1999) obtain $A \approx 0.5$, $B \approx 3.5$ for higher winds.

Applying the geostrophic drag law with the same geostrophic wind speed to another surface roughness a new friction velocity, ${u_*}'$, over the new surface is calculated. The wind in the surface layer is calculated with the help of the logarithmic wind profile [1]. Under conditions of extreme winds the surface layer is expected to be neutrally or almost neutrally stratified. Therefore, deviations of the wind profile from the logarithmic shape are expected to be very small.

Observed surface winds have to be cleaned from local influences like roughness changes within several kilometers of the site, orographic speed-up, or nearby obstacles like trees or buildings. This was done e.g. by Kristensen et al. (1999). However, as the grid size of the model is approximately 200 km, it can be assumed that the wind at 10 m is adapted to the "local" model roughness and small-scale orographic speed-up can be neglected as well.

[1] Here, I calculate the 10 m wind as $\frac{{u_*}'}{\kappa} \ln \frac{10}{0.05}$.

5.2 Roughness length used in the NCEP/NCAR reanalysis

The surface roughness used in the NCEP/NCAR reanalysis model is determined from the Simple Biosphere Model of Dorman and Sellers (1989). Daily values are interpolated from a data base of monthly values. In addition the interpolation program interpolates the data from the original $1° \times 1°$ data base to the Gaussian grid of the reanalysis model.

The roughness length of the original data base for January is shown in Figure 6. At once, a deficiency can be recognized. Although, this data base has a higher resolution than the NCEP/NCAR model, neither the peninsula of Jutland nor the Danish islands are present in it. The interpolation program `cycle` yields a land roughness for the peninsula of Jutland (Figures 7 and 8) because the land-sea mask for the NCEP/NCAR model defines these points as land areas. However, values between 0.5 m and 1 m are too high for this region, which is dominated by farming without large forest areas. In general the roughness lengths tend to be too high for the region of and near Denmark.

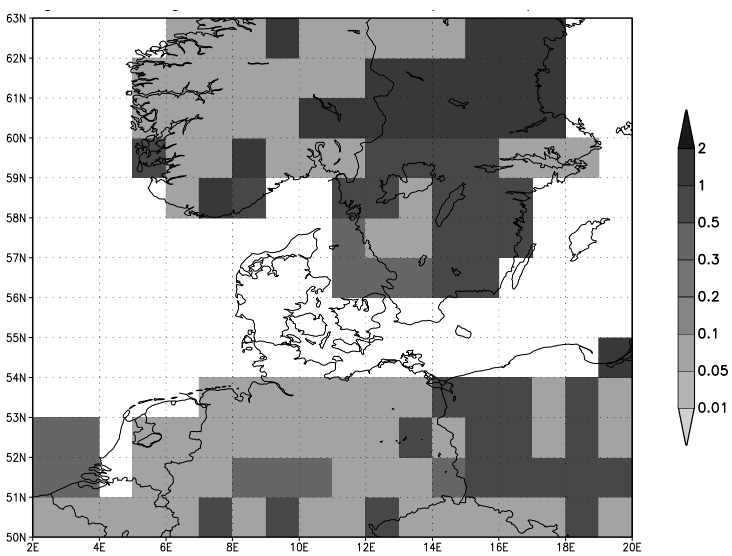

Figure 6. Surface roughness length z_0 in mid-January in the Simple Biosphere Model of Dorman and Sellers (1989). The roughness lengths in Figure 7 are derived from this data.

Over the sea the roughness length depends on the wind speed following Charnock (1955):

$$z_0 = A_c \, {u_*}^2 / g \qquad . \tag{8}$$

u_* is the friction velocity and g the acceleration of gravity. The Charnock constant $A_c = 0.014$ is used in the model (Pan, 2001).

5.3 Extreme surface wind at standard conditions

The modeled 10 m winds were transformed to the wind at 10 m above a surface with roughness length 5 cm. The friction velocity, u_*, over water can be iterated from the 10 m wind speed and Charnock's relation (8) for the sea surface roughness assuming neutral stratification for the high wind situations. Alternatively, u_* can

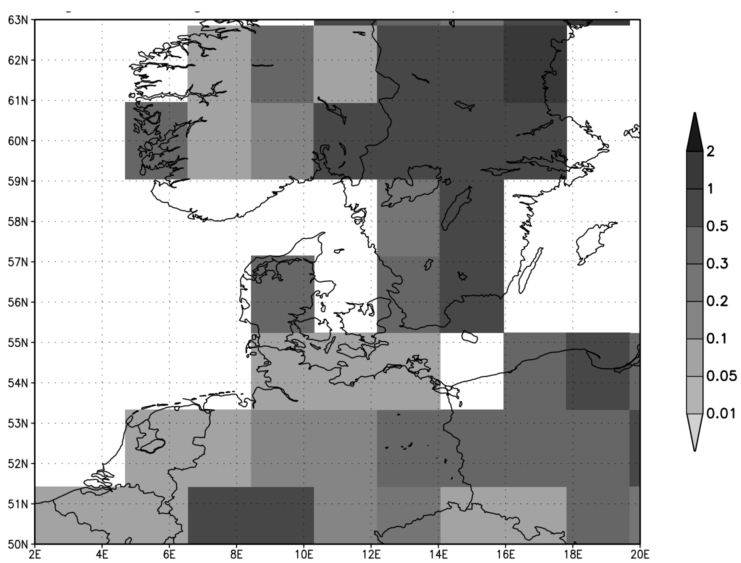

Figure 7. Surface roughness length z_0 in mid-January as used in the NCEP/NCAR reanalysis. These roughness lengths are derived from the map shown in Figure 6. The land-sea mask of the NCEP/NCAR model shows Jutland as land area. Therefore, a land roughness is generated for that grid point by the interpolation program `cycle`.

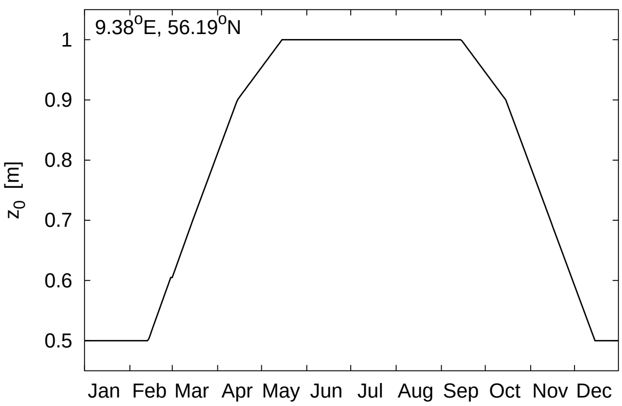

Figure 8. Annual cycle of the surface roughness length z_0 at the grid point on Jutland of the NCEP/NCAR reanalysis.

be calculated from the sea surface roughness, z_{0w},

$$u_* = \sqrt{g z_{0w}/A_c} \qquad .$$

The sea surface roughness, z_{0w}, can be downloaded from NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA. The 10 m wind was downloaded from the same site. Therefore, it was expected to be equal to the iterated sea surface roughness. Unfortunately, both methods do *not* yield the same results. The difference for the 50 years return wind is approximately 5 $\mathrm{m\,s^{-1}}$ (compare columns (1) and (3) in Table 1). Communication with Hua-Lu Pan from NCEP/NOAA and tests of the model code could not clarify the reason for the big differences. Minor differences can occur because the water roughness is updated after the calculation of the friction velocity. Then, the modeled sea surface roughness will differ from the equilibrium value in unsteady situations. However, the differences are expected to be less than 10 %.

The best result, i.e. the most uniform result, is obtained calculating the friction velocity from the down-loaded sea surface roughness and transforming this to a roughness of 5 cm. The transformed annual maximum winds were found, ordered, and the double exponential function was fitted to the records. The result is shown on the left in Figure 9. Some values are also listed in Table 1.

The roughness of water surfaces is less than 5 cm. The highest value of the down-loaded sea surface roughnesses is 3.94 mm. With $A_c = 0.014$ and $g = 9.8\ \mathrm{m\,s^{-2}}$ this roughness must be generated by a friction velocity of $1.66\ \mathrm{m\,s^{-1}}$, which yields a speed of $32.5\ \mathrm{m\,s^{-1}}$ at 10 m above the surface. However, the 10 m wind speed at this time is only $25.2\ \mathrm{m\,s^{-1}}$, which is 22.5 % less. It is not known why the sea surface roughness is so high.

The 10 m wind speed transformed to a surface with 5 cm roughness must be less than the original speed owing to the higher friction. However, if the friction velocity is calculated from the down-loaded sea surface roughness, z_{0w}, the 50-years return wind transformed to 5 cm roughness is greater than the original 50-years return wind at most grid points over water (compare Figures 5 and 9). When the friction velocity is calculated from the 10 m wind speed of the model the transformed 50-years return wind over a surface with roughness length 5 cm is approximately 5-6 $\mathrm{m\,s^{-1}}$ less than the original 10 m wind (Figure 9, right). As stated previously, the reason for the discrepancy is not known.

Over a surface with roughness length 5 cm the friction is less than over a surface with a roughness length of 50 cm. Hence, the wind over 5 cm roughness is higher than over 50 cm roughness. Therefore, the expected 50-years wind speed should decrease at the grid points over water and increases at the grid points over land. Mainly, the 50 years return wind decreases from west to east. Also, it tends to be highest near 56° N in northern Denmark and southern Sweden.

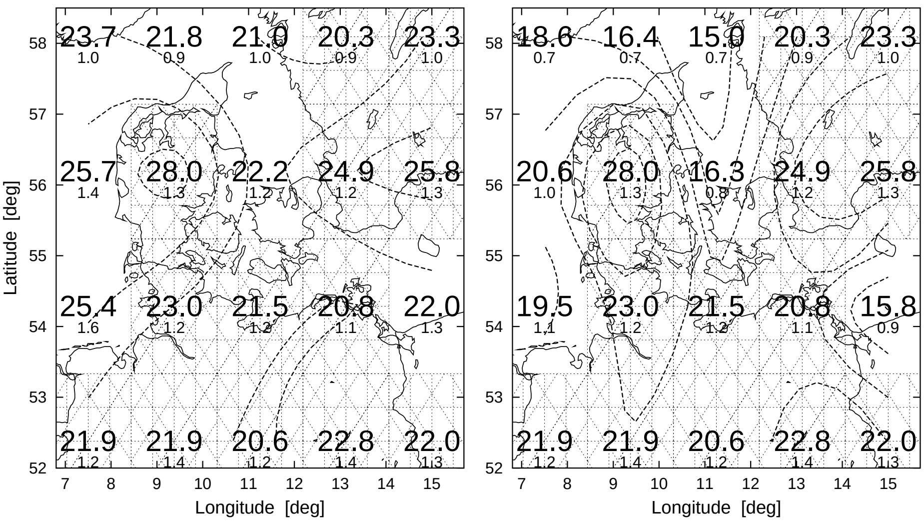

Figure 9. The expected 50-years wind at 10 m over a surface with roughness length of 5 cm determined from the NCEP/NCAR reanalysis over and near Denmark. The parameters $A = 1.8$ and $B = 4.5$ are used in the geostrophic drag law (7). Left: The friction velocity over water is determined from the sea surface roughness down-loaded from CDC, Boulder. Right: The friction velocity is iterated from the 10 m wind speed and Charnock's relation (Eq. 8).

For the transformation to 5 cm roughness length the parameters $A = 1.8$ and $B = 4.5$ were used. These are the standard values proposed in the European Wind Atlas (Troen and Petersen, 1989) and employed by the Wind Atlas Analysis and Application Program WAsP (Mortensen et al., 1993, 2000). The parameters are

Table 1. Wind speed at 10 m at grid points near Denmark transformed to 5 cm roughness length using different data sets and parameters A, B in the geostrophic drag law (Eq. 7). (1) u_* from the roughness of water down-loaded from CDC, Boulder, and Charnock's relation (8) with $A_c = 0.014$. $A = 1.8$, $B = 4.5$ in the drag law. (2) as (1), but $A = 4.0$, $B = 5.0$. (3) u_* iterated from the 10 m wind speed assuming a logarithmic wind profile and Charnock's relation for the sea surface roughness. $A = 1.8$, $B = 4.5$. (4) as (3), but using stability dependent wind profiles and the difference of the 2 m and the skin temperature.

lon deg	lat deg	sea/ land	(1)	(2)	(3)	(4)
7.5	54.285	sea	25.4	25.9	19.5	19.5
7.5	56.189	sea	25.7	26.2	20.6	20.6
7.5	58.094	sea	23.7	24.2	18.6	18.6
9.375	54.285	land	23.0	22.8	23.0	22.9
9.375	56.189	land	28.0	27.5	28.0	27.9
9.375	58.094	sea	21.8	22.3	16.4	16.5
11.25	56.189	land	21.5	21.4	21.5	21.5
11.25	56.189	sea	22.2	22.7	16.3	16.3
11.25	58.094	sea	21.0	21.4	15.0	15.1
15.0	54.285	sea	22.0	22.4	15.8	15.9

not well known, and the values of the model physics might differ from observed values. Therefore, it was attempted to determine A and B from the NCEP-model data. B was calculated from the direction of the 10 m wind, the surface roughness, and the wind at 850 hPa, or the geostrophic wind determined from the surface pressure.

$$\sin\alpha = -\frac{Bu_*}{\kappa G} \tag{9}$$

where α is the deviation of the surface wind from the geostrophic wind and the other quantities are as defined in Eq. (7). Once B is known A can be determined from (7).

All values of A and B with u_* greater than 0.4, 0.5, 0.6, etc. were averaged as in Kristensen and Jensen (1999). Unfortunately, A and B are not constant. Typically, A increases weakly with increasing u_*. Also, the values differ from one grid point to the other. At almost all grid points A is much greater than 1.8 . Therefore, the transformation was repeated using $A = 4$ and $B = 5$. Then, the 10 m wind over 5 cm roughness is increased by approximately 0.5 $\mathrm{m\,s^{-1}}$ over water and reduced over land compared to the transformation with parameter values 1.8 and 4.5 (Figure 10, Table 1). The contrast between Jutland or southern Sweden and the neighboring sea areas becomes reduced. Still, the 50-years return wind is highest at the grid point in Jutland.

Stratification has only a very minor influence on the surface winds under conditions of extreme winds (last column of Table 1). During storms the surface layer is well mixed. This was confirmed by calculations where a Monin-Obukhov-length was determined from the wind speed at 10 m and the difference of the 2 m temperature and the skin temperature of the model. The difference on the 50-years return wind is 0.1 $\mathrm{m\,s^{-1}}$ or less.

Kristensen et al. (1999) obtained 22 $\mathrm{m\,s^{-1}}$ for the 50-years return wind at 10 m over 5 cm roughness for most of Denmark. At the North Sea coast at Skjern (55.9° N, 8.4° E) they obtained higher winds of 25 $\mathrm{m\,s^{-1}}$. These wind speeds are close to the model values at 54.3° N in northern Germany and southern Denmark and to

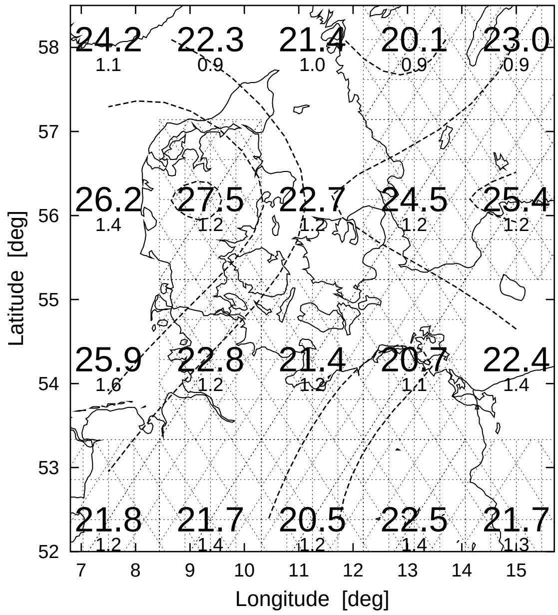

Figure 10. Expected 50-years wind at 10 m over a surface with roughness length of 5 cm using constants $A = 4$ and $B = 5$ in the drag law (7). The friction velocity at grid points over water was calculated from the sea surface roughness.

the model values at the grid points over the North Sea, when the values over water are determined from the down-loaded sea surface roughness. The speed of 28 $\mathrm{m\,s^{-1}}$ at the grid point in Jutland is too high. It seems that the unrealistically high land roughness cannot be compensated for by the transformation to 5 cm roughness. Similarly, it must be expected that the values of ca. 25 $\mathrm{m\,s^{-1}}$ for southern Sweden are too high.

The results become much worse if the 50-years winds at the grid points over water are determined from the modeled 10 m wind (Figure 9, right). Then, the 50-years return wind at standard conditions are 5–6 $\mathrm{m\,s^{-1}}$ less than above, The contrast between grid points over sea and land is as big as in the original data, only the sign of the difference is reversed. It seems that the 10 m wind over water should not be used to transform to a land roughness though the original speeds seem to be correct. The transformation should be done using the surface friction velocity which is obtained from the stored sea surface roughness.

6 Extremes of the wind at 850 hPa

6.1 Wind at 850 hPa

The previous result was disappointing for Jutland which is the major part of Denmark. The problem with the correct friction velocity over water could not be resolved. Therefore, an extreme wind analysis was done for the wind at the 850 hPa level. Generally, this level is above the planetary boundary layer in Denmark. Therefore, it is not directly influenced by the surface roughness.

The wind at 850 hPa is close to the geostrophic wind at 850 hPa. However, it must be expected that the geostrophic wind, i.e. the pressure gradient, at the surface is greater than at the 850 hPa level. Cyclones deepen at the surface in agreement with theoretical models of cyclogenesis (e.g. Hoskins, 1982, or Figures 13 and 15). The 850 hPa wind is used here because it is an analyzed quantity strongly influenced by observations, and no additional calculations are needed to get it.

The highest wind at 850 hPa plus its date of occurrence is shown in Figure 11. In general the highest winds decrease towards northeast. The dates of the highest wind at 850 hPa differ from those of the highest surface wind (compare Figures 11 and 2).

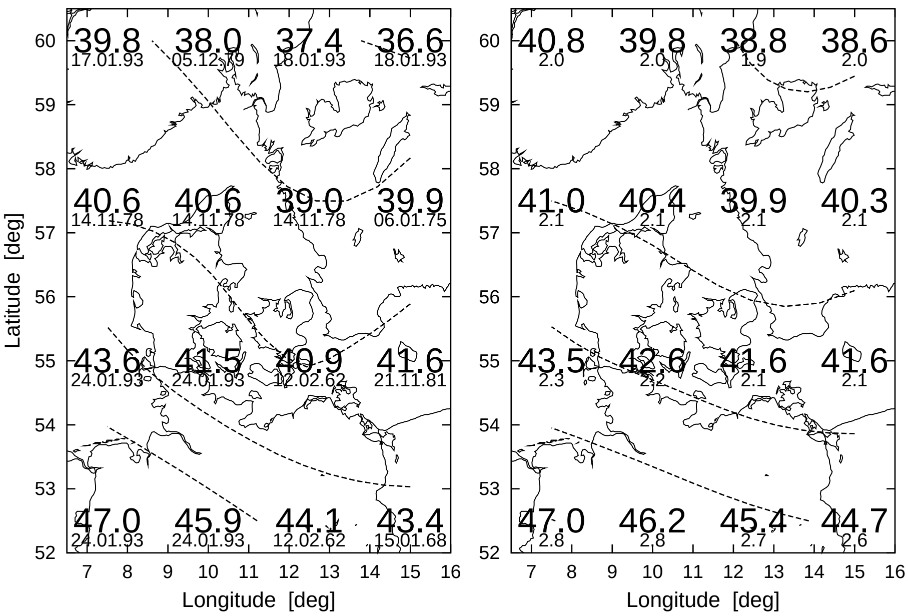

Figure 11. Left: Maximum wind at 850 hPa for the years 1948 to 1999 of the NCEP/NCAR reanalysis and date of the maximum wind. Right: Expected 50-years wind at 850 hPa and standard deviation of the expected value.

The 50-years return winds are very similar. The extreme winds decrease from southwest to northeast. The main variation is in south-north direction.

6.2 Extreme surface wind derived from wind at 850 hPa

We assume that the wind at 850 hPa is almost equal to the geostrophic wind. Hence, it can be transformed to a surface wind using Eq. (7). The resulting surface winds are half as strong as the winds at 850 hPa (Figure 12). They are approximately 2 $\mathrm{m\,s^{-1}}$ less than the values obtained by Kristensen et al. (1999) for the central and eastern part of Denmark. However, if we introduce the correction factor 1.1 (see section 4) to account for the low temporal resolution, essentially the same extreme winds are obtained.

The trend from west to east agrees with the conclusion of Kristensen et al. (1999) that the west coast of Denmark experiences higher winds than the rest of the country. However, owing to the low resolution of the model, and perhaps enhanced by the smoothing to the 2.5 degree grid, the difference is very small. The difference between southern and northern Denmark is bigger in the model results. Unfortunately, Kristensen et al. did not analyze data in northern Jutland. The mean winds at the northern tip of Jutland are less than along the west and northwest coast (Mortensen et al., 2001). This might indicate that the extreme winds are also weaker.

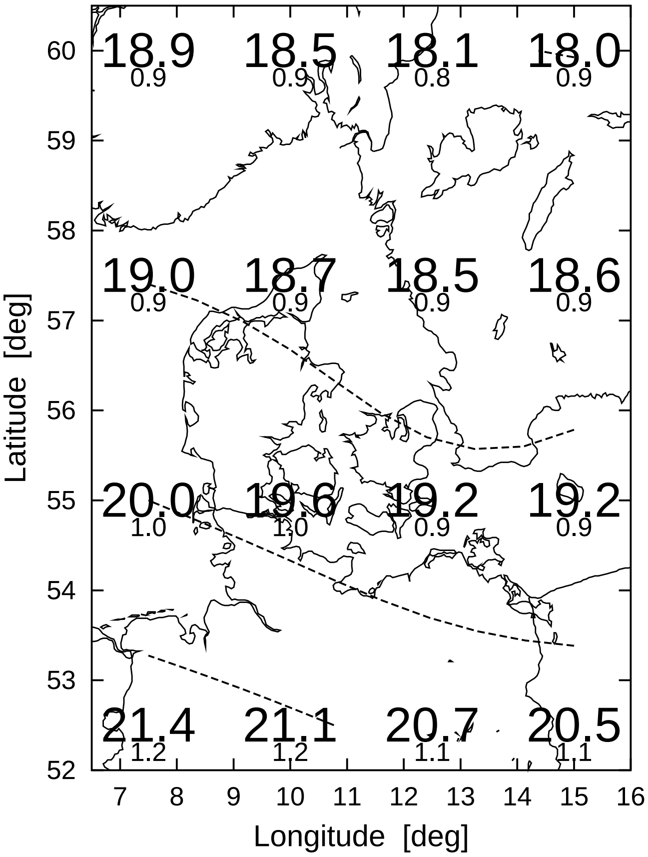

Figure 12. Expected 50-years wind at 10 m above a flat surface with roughness length 5 cm obtained from the wind at 850 hPa using the geostrophic drag law (Eq. 7).

7 Extremes of the geostrophic wind

7.1 Geostrophic wind

Since the geostrophic drag law is being used to transform surface winds to the same conditions, we might as well start directly with the geostrophic wind. In this section the extreme wind analysis is carried out for the geostrophic wind calculated from the geopotential height Z of the 1000 hPa or 850 hPa pressure surface, or from the surface pressure, p_s:

$$u_g = -\frac{g}{f}\frac{\Delta Z}{R\Delta\phi} \tag{10}$$

$$v_g = \frac{g}{f}\frac{\Delta Z}{R\sin\phi\Delta\lambda} \tag{11}$$

$$u_g = -\frac{1}{f\rho}\frac{\Delta p}{R\Delta\phi} \tag{12}$$

$$v_g = \frac{1}{f\rho}\frac{\Delta p}{R\sin\phi\Delta\lambda} \tag{13}$$

where u_g and v_g are the components of the geostrophic wind, R is the radius of the earth, ϕ is latitude, and λ is longitude, and ρ is the air density. p is the surface pressure extrapolated to sea level. The geostrophic wind components at the pressure levels were calculated in between the grid of the geopotential with

$\Delta\phi = \Delta\lambda = 2.5°$. The geostrophic wind at sea level was calculated at the grid points across $2\Delta\phi$ or $2\Delta\lambda$. But, for the surface data $\Delta\phi = 1.875°$, and $\Delta\lambda \approx 1.9°$. Only data at 00 UTC and 12 UTC for the 47 years 1953-1999 were analyzed.

The 1000 hPa surface lies at a mean height of 100 gpm (geopotential meters) to 120 gpm. Therefore, it had been extrapolated from greater heights at some grid points. Also, in deep pressure lows the 1000 hPa level will be below sea level.

The highest geostrophic wind plus date of occurrence is shown in Figures 13 and 15. At many points the highest geostrophic wind at 1000 hPa is approximately 2 $\mathrm{m\,s^{-1}}$ greater than at 850 hPa. In the western part of our area of investigation the strongest geostrophic wind calculated from the surface pressure field is greater than the geostrophic wind calculated from the 1000 hPa level. In the south-eastern part the geostrophic wind from the surface pressure is less than the geostrophic wind from the 1000 hPa level. At many points the geostrophic wind is greater than the actual wind at 850 hPa (compare Figures 11 and 13). This is not astonishing because the highest pressure gradients occur in cyclones. There, the actual wind is closer to the gradient wind, a balance between pressure gradient, Coriolis, and centrifugal force. The gradient wind is less than the geostrophic wind in cyclones.

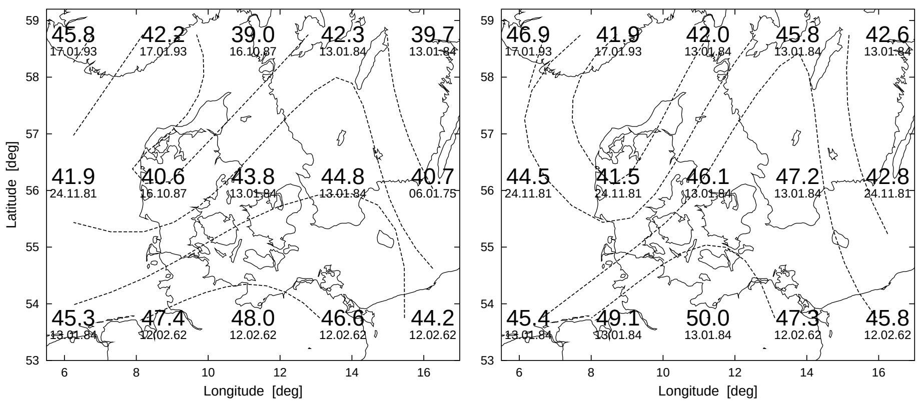

Figure 13. Maximum of the geostrophic wind at 850 hPa (left) and 1000 hPa (right) for the years 1953 to 1999 of the NCEP/NCAR reanalysis and date of the maximum wind.

The expected 50-years geostrophic wind is shown in Figures 14 and 15. The 50-years geostrophic winds calculated from the constant pressure levels are practically constant from west to east across Denmark. Unexpectedly, the 50-years geostrophic wind is higher northwest as well as south of Denmark. The lowest values occur towards the northeast over central Sweden. The 50-years geostrophic wind is 0.2-1 $\mathrm{m\,s^{-1}}$ weaker at 850 hPa than at 1000 hPa, except in the very SE corner of Figure 14.

The variation of the 50-years geostrophic wind calculated from the surface pressure (Figure 15) looks much more as expected decreasing from west to east. The highest winds are predicted for the southern North Sea and the lowest winds for central Sweden and north-eastern Germany.

7.2 Extreme surface wind derived from geostrophic wind

The geostrophic wind transformed to a wind at 10 m above a surface with roughness length 5 cm is shown in Figure 16. The value over Jutland is very close to the surface wind obtained from the wind at 850 hPa. In northern Germany and Southern Norway the surface wind obtained from the geostrophic wind is greater

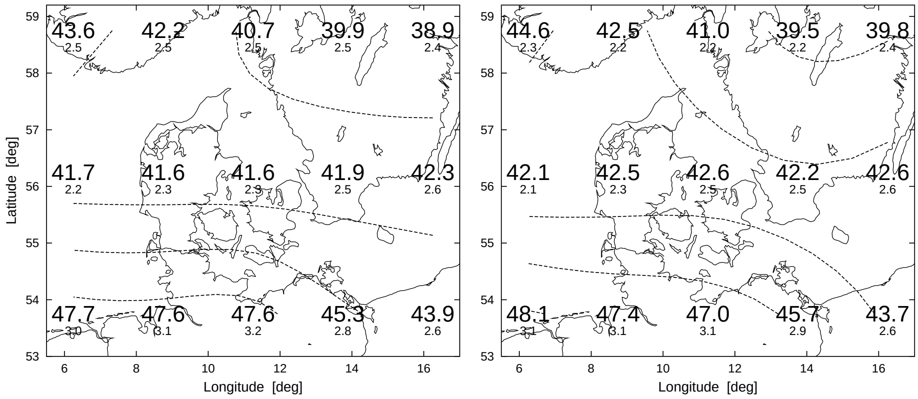

Figure 14. Expected 50-years geostrophic wind at 850 hPa (left) and 1000 hPa (right).

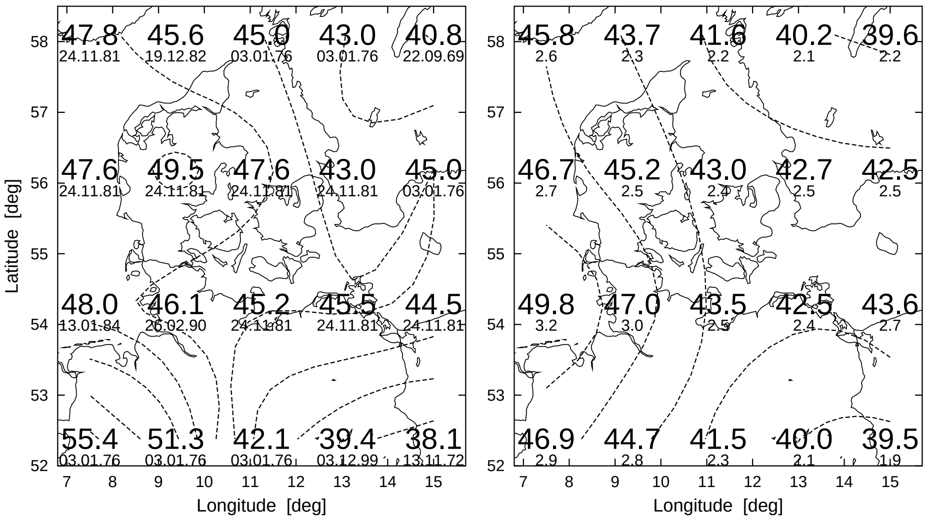

Figure 15. Maximum of the geostrophic wind at sea level (left) and of the expected 50-years geostrophic wind at sea level (right).

than from the wind at 850 hPa.

Considering the error margins the analysis of the geostrophic wind on constant pressure surfaces yields constant extreme winds for Denmark. There is no indication for greater winds near the Danish west coast as found by Kristensen et al. (1999).

The 50-years wind calculated from the surface pressure shows the expected decrease from west to east. The values are approximately 10 % less than the 22 $\mathrm{m\,s^{-1}}$ found by Kristensen et al. (1999) for most of Denmark. Unfortunately, we have no observations to verify that the highest winds are in the southern North Sea. Overall the pattern obtained from the surface pressure looks more realistic than from the geostrophic wind at the constant pressure levels. Perhaps, the interpolation to the 2.5° grid had smoothed the data too much.

8 Conclusions

Unfortunately, it seems not possible to compare the extreme winds at 10 m of the NCEP/NCAR reanalysis with observed extreme winds over Denmark. The

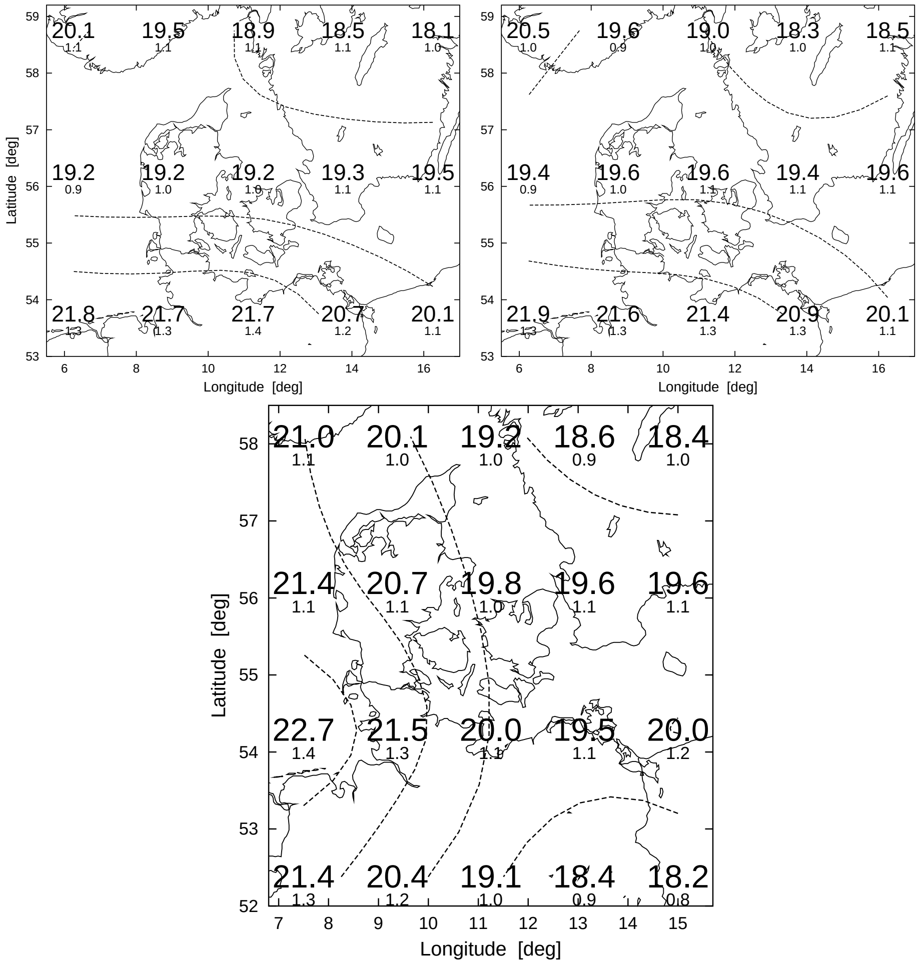

Figure 16. Expected 50-years wind at 10 m above a flat surface with roughness length 5 cm obtained from the geostrophic wind at 850 hPa (top left), at 1000 hPa (top right), and the geostrophic wind at sea level (bottom) using the geostrophic drag law (Eq. 7).

roughness length used in the NCEP/NCAR reanalysis at land points in Denmark is much to high. At some grid points — in the North Sea west of Denmark, perhaps in northern Germany — the expected 50-years return winds seem to compare well with other investigations based on surface measurements if the reanalysis values are increased by approximately 10–12 % owing to the low spatial and temporal resolution of the model data.

The analyses of the wind at 850 hPa and the geostrophic wind at 850 hPa and 1000 hPa yield very similar extreme winds of approximately 42 $\mathrm{m\,s^{-1}}$. The surface pressure data yields extreme geostrophic winds of ca. 45 $\mathrm{m\,s^{-1}}$ over Jutland. Transformed to a height of 10 m above a surface with roughness length 5 cm we obtain approximately 20 $\mathrm{m\,s^{-1}}$ for the 50-years return wind. This is approximately 10 % less than found by Kristensen et al. (1999) for most of Denmark. Considering the low temporal and spatial resolution of the model data such an underestimation could be expected.

The surface wind, the wind at 850 hPa, and the geostrophic wind calculated from the surface pressure indicate a weak decrease of the extreme winds from western to eastern Denmark. This could be some indication for the observed rougher wind climate along the Danish west coast as found by Kristensen et al. (1999). The geostrophic wind data on constant pressure levels indicate constant values across

Denmark.

A comparison with extreme wind analyses in other areas of the mid-latitudes would be necessary to find out if the underestimation of the "true" extreme winds by 10–12 % in the reanalysis data is generally valid. Compared to the resolution of the reanalysis model, and perhaps also compared to the size of most cyclones, Denmark is just too small to see big differences across the country.

In our opinion the analysis indicates that the best estimate for extreme winds in mid-latitudes can be obtained from geostrophic wind calculated from the surface pressure field. The 10 m wind speed is influenced strongly by the surface roughness of the model. It should be checked if the surface roughness at the grid points in question is realistic before the 10 m wind is used. In areas with big variations of the surface height it is difficult to calculate correct horizontal pressure gradients. There it might be best to use an upper-air wind, e.g. at 850 hPa, with a greater correction factor than for the geostrophic wind at the surface.

In further work the extreme wind rose for different wind direction sectors can be determined. Also, it was not investigated, what is the difference between the geostrophic wind and the gradient wind.

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Figures 1, 6, and 7 were made using the GrADS software by B. Doty.

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A Appendix

The ordered one-year maximum wind speed at 10 m and the double exponential fit are shown in the following figures. Thin lines are the fit plus/minus one standard deviation.

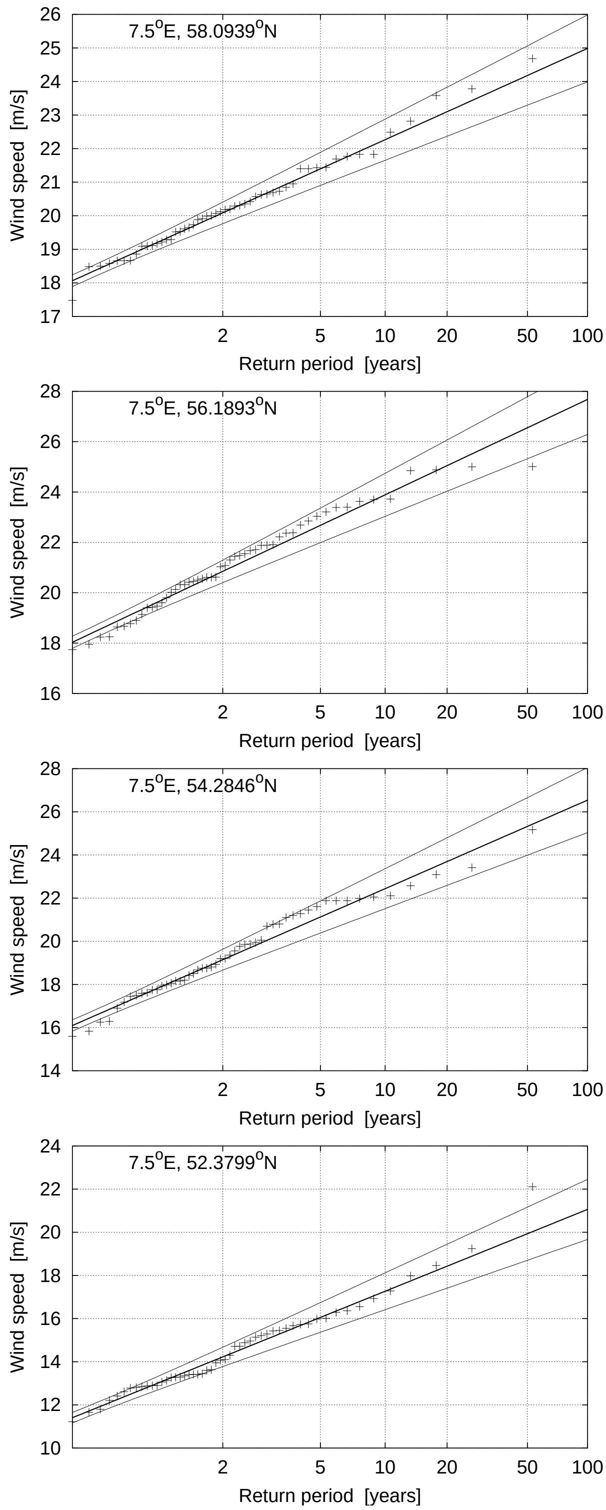

Figure 17. Annual maximum wind speeds at 10 m at 7.5° East and double exponential fit.

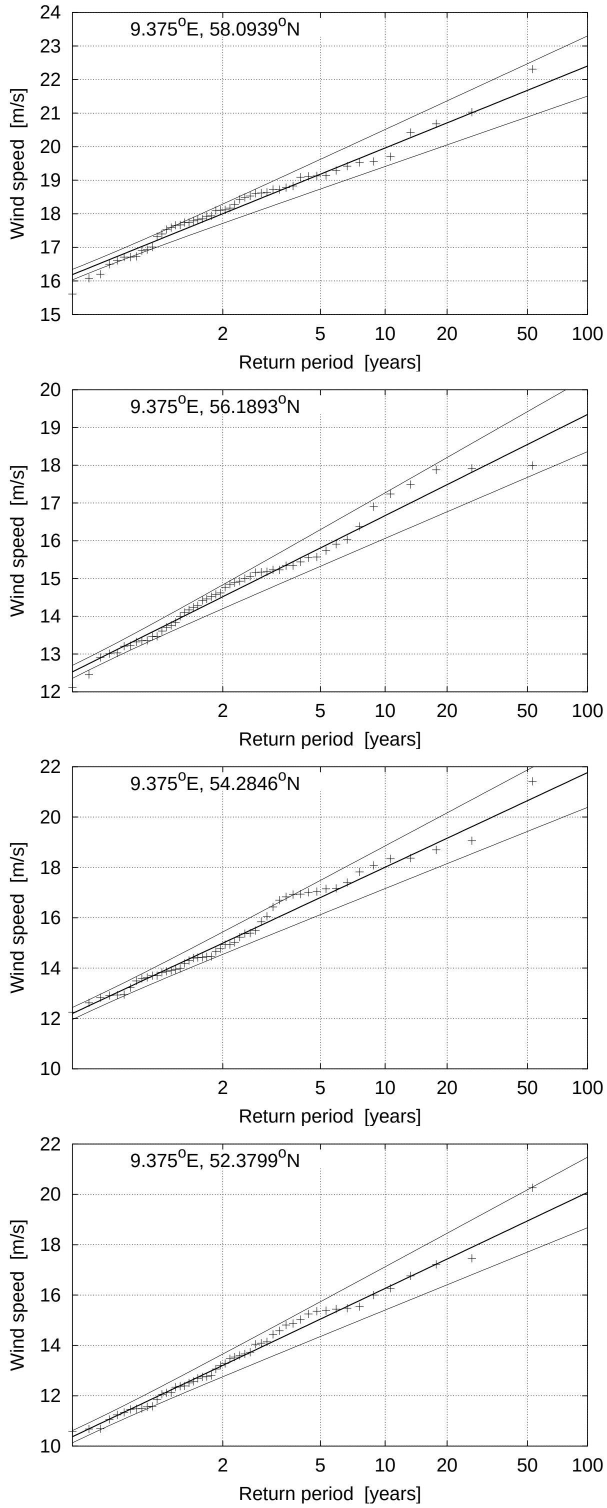

Figure 18. Same as Figure 17 at 9.375° *East.*

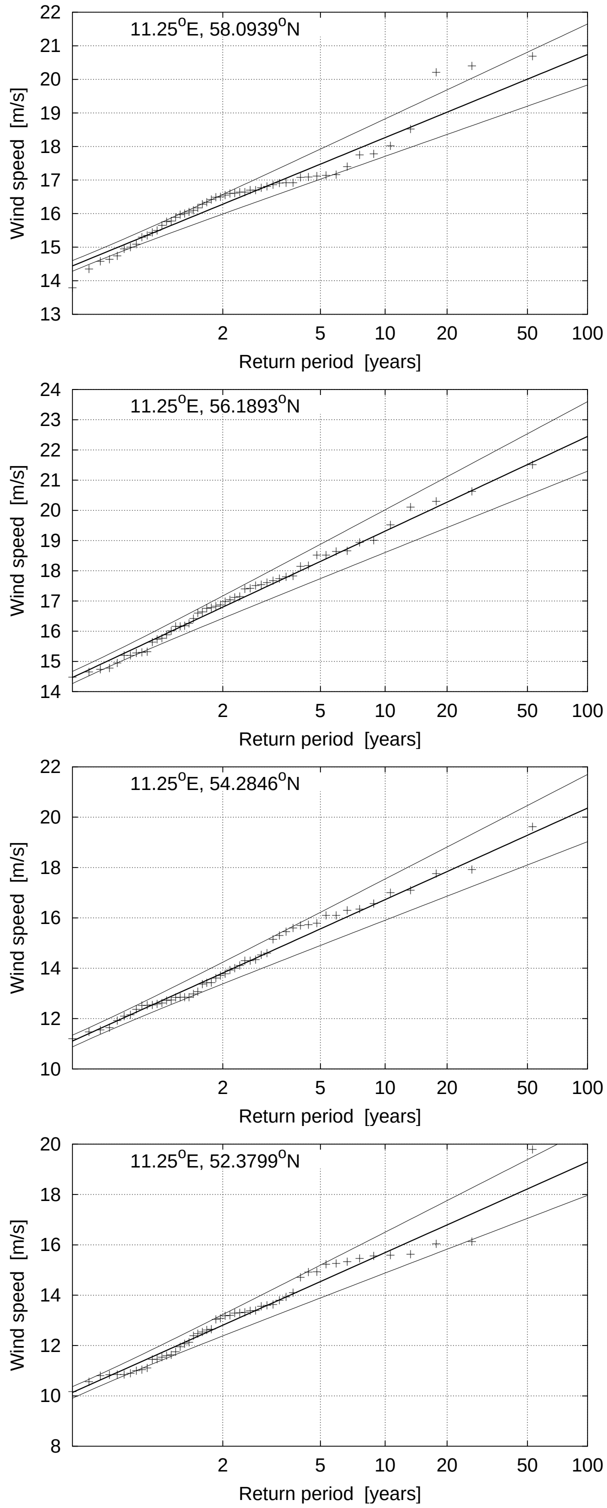

Figure 19. Same as Figure 17 at 11.25° *East.*

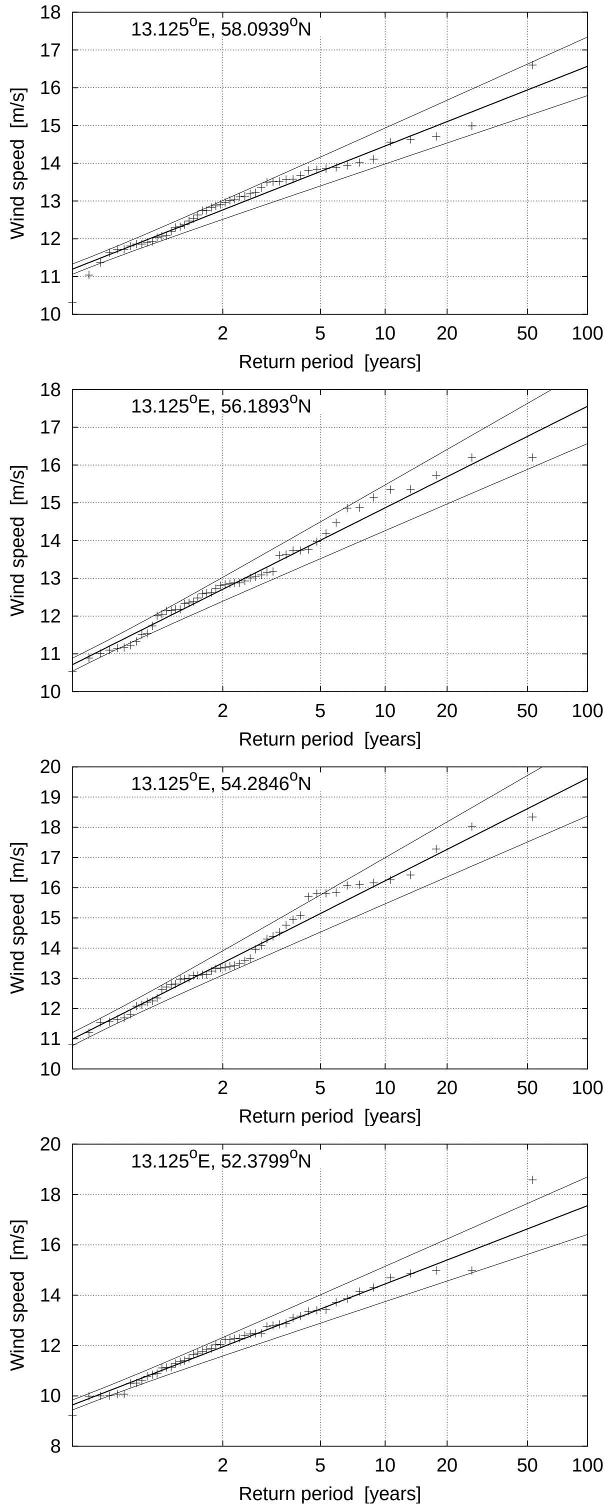

Figure 20. Same as Figure 17 at 13.125° *East.*

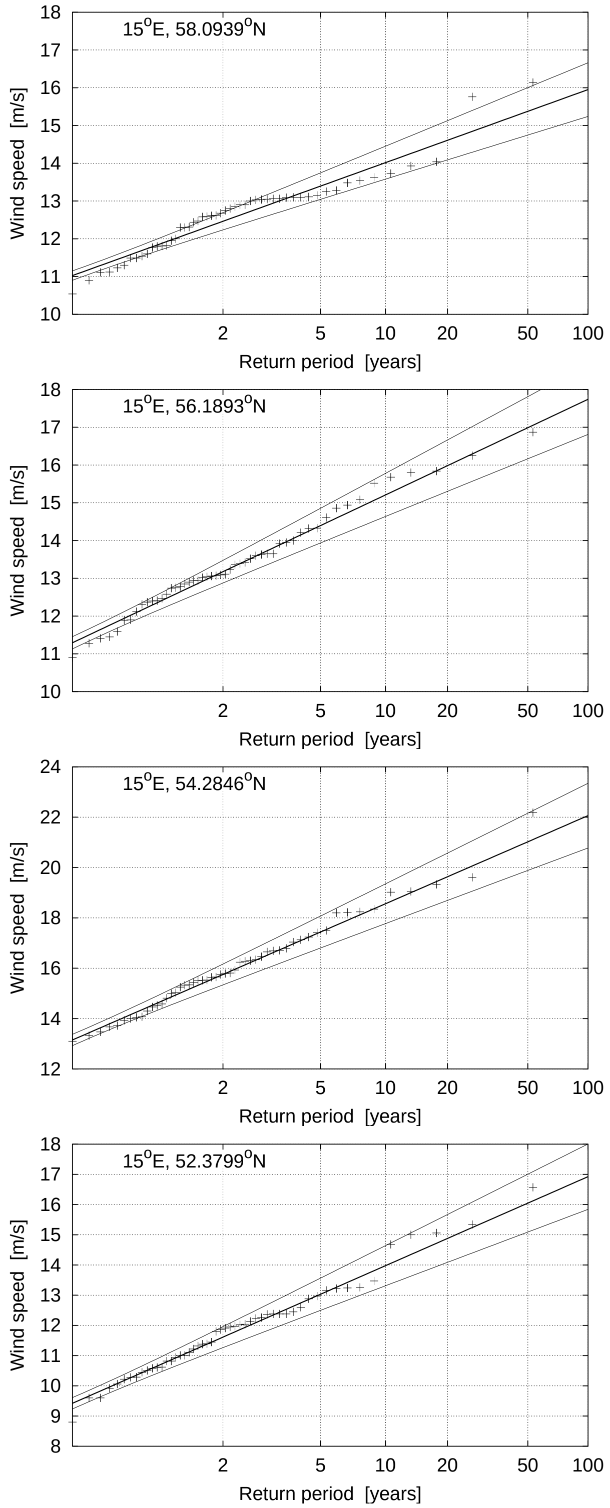

Figure 21. Same as Figure 17 at 15° East.

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Extreme Winds over Denmark from the NCEP/NCAR Reanalysis

Helmut P. Frank

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Abstract (Max. 2000 char.)

An extreme wind analysis of wind speed calculated in the NCEP/NCAR reanalysis is done for grid points over and near Denmark. Winds at 10 m, 850 hPa, and geostrophic winds at 850 hPa, 1000 hPa, and at the sea level are analyzed.
At 10 m height the expected extreme wind with a return period of 50 years at the North Sea west of Denmark is 27 $\mathrm{m\,s^{-1}}$. It is approximately 11 % less than estimates from observations. However, values at grid points over land in Denmark cannot be compared with observations because the roughness length of these land surfaces is far to big in the model. A transformation to a common roughness length of 5 cm using the geostrophic drag law yields too high values. At points in northern Germany, where the surface roughness of the model is less, the transformed 50-years wind speed is 22–23 $\mathrm{m\,s^{-1}}$, which agrees well with estimates obtained from measurements.
The analyses of the wind at 850 hPa and the geostrophic wind at 850 hPa or 1000 hPa yield very similar extreme winds of approximately 42 $\mathrm{m\,s^{-1}}$. The geostrophic wind calculated from the surface pressure is approximately 45 $\mathrm{m\,s^{-1}}$ in central Denmark. The geostrophic winds at 1000 hPa are slightly stronger than at 850 hPa, which are somewhat greater than the actual wind at 850 hPa. Transformations to a wind at 10 m over a surface with roughness 5 cm with the help of the drag law yield extreme winds, which are approximately 10–12 % less than from surface measurements. The 850 hPa winds and the geostrophic wind calculated from the surface pressure indicate a weak decrease from west to east, whereas the geostrophic wind data at constant pressure levels show almost constant extreme winds across Denmark. All upper-air and and geostrophic wind data show higher extreme winds in northern Germany than in Denmark.
Further investigations are necessary to find out if the underestimation of the extreme wind by approximately 10–12 % is valid in most mid-latitudes.

Descriptors INIS/EDB

DATA ANALYSIS; DENMARK; MATHEMATICAL MODELS; STORMS; VELOCITY; WIND

Available on request from:
Information Service Department, Risø National Laboratory
(Afdelingen for Informationsservice, Forskningscenter Risø)
P.O. Box 49, DK–4000 Roskilde, Denmark
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